A Robust Closed-Loop Gait for Humanoid Clock-Turning

Nima Shafii, Abbas Abdolmaleki, Nuno Lau, Luis Paulo Reis

Abstract—Turn-in-place or clock-turning is a basic motion in humanoids robots path planning, however, it can be considered as one of the most complicated tasks in biped locomotion studies. A biped robot needs to move all leg joints in all three -transverse (axial), frontal (lateral) and sagittal -planes. This paper presents a model-free approach based on Fourier series to generate walking trajectories, both, in the foot positional space and the joint angular space. By using trunk stability, our emphasis is on making a robot perform "Clock-Turning" motion more stable and fast. A Genetic algorithm was used to optimize joint trajectories produced by Truncated Fourier Series (TFS) in the simulation environment. Finally, Hill Climbing optimization is obtained on real robot to find locally optimal gait in foot positional trajectories. Multiple experiments were conducted to demonstrate the effectiveness of the proposed method on simulated and real robot.

Keywords: Bipedal Locomotion, Gait Generation, Gait Optimization.

I. INTRODUCTION

Humanoid robots are organized in a human-like fashion; they have to deal with dynamic constraints such as balance, as well as geometric constraints. They have larger number of joints (redundancy) which makes them more attractive to researchers. While wheeled robot locomotion is not adapted to many human environments such as, stairs and areas littered by many obstacles, this redundancy enables humanoid robots to avoid obstacles, joint limits, and attain more desirable postures. Therefore, by using biped locomotion, humanoid robots can function and perform their tasks easier than wheeled robot in areas designed for people. In the future, biped robots should have ability to maneuver easily in any environment.

Therefore, besides forward walking, other motions like beside walking and turning should come into research interests of biped locomotion researchers. Biped robots to reach a destination need to change their direction to avoid obstacles or following an specified path in most scenarios. Kuffner et al [1] proposed an online footstep planning method for biped robots to move and avoid obstacles in environment. This work mostly is focused on obstacle avoidance for robot where the balance and locomotion is not the matter. Kajita et al. [2] proposed a method to control humanoid walking motion. Their method was based on a simplified 3D inverted pendulum model (LIPM), which overlooked substantial dynamics of robots and has constraints for planning to move the center of mass, e.g. it can't model to move the Center of Mass (CoM) in Z axis. He also presented a turning gait planning, in which the objective of turning is to follow a curve with certain radius [3]. This is called forward-turning or curving. The aim of clock-turning is to change robot's direction at a fixed position. These two kinds of turning are suitable in different situations, due to the fact that in forward-turning, there are no switches between different motion gaits during the whole obstacle avoidance. In this case, robots require more prediction and consideration of accurate position and shape of obstacles. But, clock-turning is able to combine turning and walking to adapt to different shapes of obstacles. Therefore, clock-turning has lower requirements for the humanoid sensor system. Although the clock-turning has been used as a basic motion for humanoid global path planning, there is only one previous work on it [4]. In 2007 Tang et al. tried to investigate turn motion by using linear inverted pendulum model , and preview control of the zero momentum point (ZMP) indicators and inversed kinematics[4]. Like other 3D LIPM approaches, one of the main issues, is that they cannot produce running and jumping movements since it models the support leg as the massles telescopic leg.

In our previous studies [5][6][7], we employed Fourier series and evolutionary algorithms like genetic and PSO algorithm to generate angular trajectory for bipedal direct walking and we verified our method through simulation and experimental results. This method has three significant advantages. First of all, it can be used for every humanoid robot without any mathematical modeling, so in our previous work we called it a model free approach. Second this approach has a low computational complexity and can be implemented on real humanoid robots, which the response of controller should be real time. Finally Fourier series can parameterize a signal well; therefore robot locomotion controller designer can manipulate signals simply by changing parameters of Fourier series in proper times. In addition, the last advantage leads utilizing optimization algorithms to achieve the best parameters of Fourier series to generate proper control signals for locomotion gate planning.

In this paper, a new model-free approach for turning-in-place is proposed. In this method, Fourier series are used to model joints angular trajectories on the simulated robot. Genetic algorithm is used to optimize the parameter of the model on the simulated robot.

Learned trajectories of simulation results are reconfigured

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again in order to apply on the real robot. Fourier series is used to remodel the movement of the knee for support leg of a real robot in foot positional space. This can lead us to produce the movement of the CoM in Z axis. A sensory feedback based on the High frequency response to the torso accelerometer is also implemented, in order to have the trunk stability control on the sagittal plane. Hill climbing as a local search technique is applied to optimize parameters of the model on a real robot.

II. TURN ANGULAR TRAJECTORIES

As it was mentioned, First we test our method on a simulated humanoid robot and then simulation results are transferred to a real robot. The robot model in this study is the NAO robot and the simulation is performed by Rcssserver3d [8]. The robot model has 22 DOFs with a height of about 57cm, and a mass of 4.5kg. Schematic view of our humanoid robot is shown in fig. 1. DOFs 2,3, and 4 move on Sagital plane and DOFs 1 and 5 move in Frontal plane while DOF 6 moves on transverse plane.

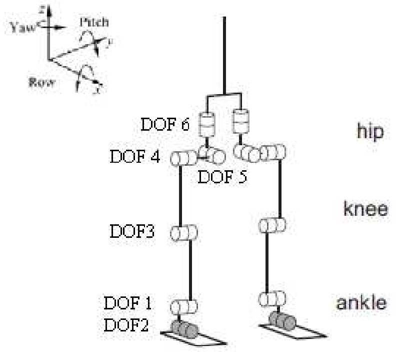

Fig. 1. Schematic view of the lower body of the humanoid robot

Human turn motion can be investigated in many aspects; turning trajectory used here is divided into two types: Positional trajectory and angular trajectory. Foot positional trajectory and Joints Angular trajectory. Angular trajectories provide the angle of each joint at each time slice. In order to achieve the shape of angular trajectory of a turning motion, we start by analyzing angular trajectories results from previous works based on the 3D LIPM approach, which was explained in the introduction and can be found in [4]. Biped angular trajectories of two joints; hip and knee in sagittal, frontal and transverse plane from a humanoid turning are shown in Fig 2,3 and 4 respectively.

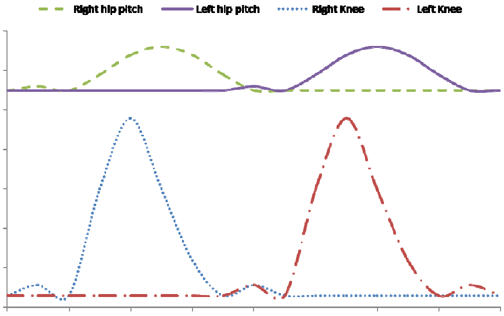

Fig. 2. Hip angle trajectories in sagittal,frontal and transerve planes

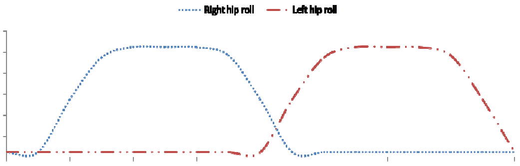

Fig. 3. Knee angle trajectories in sagittal plane

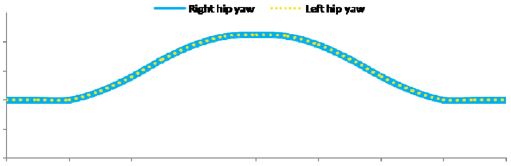

Fig .4 Hip angle trajectory in transverse plane

Since a gait is a cyclic, periodic motion of the joints of a legged robot, it requires the sequencing and coordination of the legs to obtain reliable locomotion. In other words, gait is the temporal and spatial relationship between all the moving parts of a legged robot [13]. Therefore, all gaits angular trajectories are periodic and Fourier Series can be used to model and generate the mentioned trajectories.

In the following sections, we explain how to generate references trajectories for these DOFs in mentioned planes separately to achieve a stable turn-in-place motion for humanoid robot.1

A. *Movements in Sagittal Plane*

As mentioned in previous sections, there are three DOFs in each leg which move on sagittal plane; one in the hip, one in the ankle and one in the knee. The model for generating angular trajectories in sagittal plane is very similar to Truncated Fourier series (TFS) model which was presented in 2009 [5]. In that work, similar to [7], foot in sagittal plane was kept parallel to the ground by using ankle joint. This is done in order to avoid collision. Therefore, ankle trajectory can be calculated by hip and knee trajectories and ankle DOF parameters are eliminated.

In that model, and also according to Fig.2 and Fig. 3. each signal has an offset. In addition, the trajectories for both legs are identical in shape but are shifted in time relative to each other by half of the turning period. So by producing trajectory of one leg the other leg's trajectory can be calculated. The Fourier Series (FS) for generating hip and knee trajectories in sagittal plane are formulated as below "(1),"

$$\theta_{hx} = A_{hx} \,.\, \sin(w_{hx}\, t) + C_{hx}\,,\; W_{hx}= \frac{2\pi}{T_{hx}}$$
$$If(\theta_{hx} < C_{hx})$$
$$\theta_{hx} = C_{hx} \qquad (1)$$

$$\theta_{k} = A_{k} \,.\, \sin(w_{k}\, t) + C_{k}\,,\; W_{k}= W_{hx}$$
$$If(\theta_{k} < C_{k})$$
$$\theta_{k} = C_{k}$$

In these equations, A_{hx} and A_k are constant coefficients for generating signals. The h_x and k index stands for hip and knee in sagittal plane respectively. Also C_{hx} and C_k are signal offsets and T_{hx} is assumed the period of hip trajectory. As it is mentioned in [4], all joints except "hip yaw" joint have equal movement frequency and the frequency of Fourier Series (FS) for "hip yaw" joint is half of other joints. Therefore, the $W_{hx}= W_{k}= 2\pi/T_{hx}$ equation can be derived. Fourier series parameters in sagittal plane are A_{hx}, A_k , $C_{hx,}$ C_k and W_{hx}..

B. Movements in Frontal plane

Each leg has two DOFs which locomote on Frontal plane; in hip and ankle. the hip roll angular trajectory in a single turning period was illustrated in Fig.2. Similar to sagittal plane, foot stays parallel to the ground. To do so, angle of ankle in frontal plane stays equal to hip´s angle of the opposite leg. So the trajectory of ankle in frontal plane can be derived from the trajectory of hip angle in frontal plane. Shafii et.al also modeled a similar movement in frontal plane by the TFS [6]. The Fourier Series formula for generating hip trajectories in frontal plane is as follows "(2)".

$$\theta_{hy} = A_{hy} \,.\, sin(w_{hy}\, t) \;,\; W_{hy} = W_{hx} = \frac{2\pi}{T_{hx}}$$
$$If(\theta_{hy} < 0) \qquad (2)$$
$$\theta_{hy} = 0$$

The above formula, h_y index representing hip in frontal plane. A_{hy} and W_{hy} are amplitude and frequency of signal respectively. T_{hy} is period of hip in frontal plane. period of hip signal in frontal plane and sagittal plane are equal. W_{hy} is eliminated from our unknown parameter set. Correct value of A_{hy} parameter must be found.

C. Movements in transverse plane

The hip DOF allows moves on the tranverse plane. As has been shown in Fig.4, for both legs the signal for this joint is the same, so we need to determine the parameters of one leg. The NAO robot also has on actuator in order to move in transverse plane. The Fourier Series equations that generate hip trajectory in the transverse plane is formulated below "(3)".

$$\theta_{hr} = A_{hr} \,.\, sin(w_{hy}\, t) + C_{hr} \quad W_{hr} = W_{hx}/2 = \frac{\pi}{T_{hx}}$$
$$If(\theta_{hr} < C_{hr}) \qquad (3)$$
$$\theta_{hr} = C_{hr}$$

In these equations, A_{hr} is constant coefficient for generating signal. The hr index stands for hip in transverse plane. Also C_{hr} is signal offset. As it is mentioned, the movement frequency of FS for hip yaw joint is half of other joints, so the $W_{hr}= W_{hx}/2$ equation can be concluded. Therefore, W_{hr} can be achieved from $W_{hx,}$ and It is eliminated from parameters to be found . Consequently, A_{hr} and C_{hr} should be determined. So parameters of Fourier series to generate proper angular trajectories for turn-in-place motion are $A_{hx,}$ $A_{hy,}$ $A_{hr,}$ A_k, $C_{hx,}$ $C_{hr,}$ C_k, W_{hx} And an optimization algorithms must optimize the 8 dimensions problem to find the best turn gate generator in this stage.

D. Genetic Algorithms For Optimizing Trajectories On the simulated robot

Genetic Algorithms (GA) is a stochastic searching procedure based on the mechanics of natural selection and genetics [9]. GA is used to find the best parameters to generate angular trajectories for robot turning motion. To follow these angular trajectories all individual robot joints are controlled by using proportional derivative (PD) controllers.

Truncated Fourier Series (TFS) has 8 parameters to generate all joints angular trajectories, thus each chromosome has 8 Genes, In Designing of Chromosomes gene's type is considered as double format. Population for each generation is assumed to be 100.

Equation 4 shows fitness function formulation, where the robot is initialized in x=y=0 (0,0) aligned to the horizontal axis where *rotdegree=0* and time duration for turning is 60 *s.*

`Fitness = rotdegree - 90*dist`

In the above equation the *rot degree* is the amount of turning at radian and *dist* is the amount of movement from initial place. The GA optimization has been configured with a scattered function for the cross over operator. For mutation, a uniform function has been with mutation rate is assumed 0.06.

Selection method is roulette wheel and reproduction rate is assumed as 0.8.

7 hours after starting GA on a Pentium IV 3 GHz machine with 2 GB of physical memory, the number of generations was 28 and the robot could turn in place 360 degree in 4s with average body speed of around 90 degree/s. In below figures angular trajectory generated by TFS after learning process are shown.

III. REMODEL LEARNED TRAJECTORIES IN ORDER TO APPLY ON THE REAL ROBOT

Gait optimization, using a Genetic algorithm, led the simulated robot to learn how to turn in place. Every Physical simulator contains some simplifications in its real world model; therefore the results of simulation and reality are usually not the same. However, current simulators are quite precise and simulation results have many similarities with those obtained in the real world. This issue is called the reality gap. The reality gap is smaller if the behavior is executed at slow speeds; also the stability of most behaviors is enhanced when using lower speeds.

According to [10] smaller gait with lower amplitude has lower speed and acceleration than bigger gait with higher amplitude. In order to reduce the speed of turn motions, all angular trajectories of the legs (learned by simulation) can be multiplied by a variable assumed as *K*. The value of this variable can range from zero to one. Zero value produces the lowest speed, the robot will be stopped, and one produces the same trajectories determined by the simulation. The *K* value can be found by any local search techniques.

The specification of TFS approach, by defining each joint trajectory independently from the others, does not provide a good model for controlling the foot trajectory. To achieve a more controllable model, the TFS approach specification is converted to use the Leg interface.

Leg interface was presented in 2006. The behavior uses a leg interface to control the leg movements. The leg interface allows specification of the leg positions by using three components: leg angle, leg extension and foot angle. [11]

Leg extension γ is assumed to be the distance between the hip and the ankle. It can be normalized in the range of -1 and 0, $-1 \leq \gamma \leq 0$, where $\gamma = -1$ denotes that the leg is fully extended and $\gamma = 0$ denotes the leg is shortened.

With this new model it is easy to control foot height trajectory. changing the leg extension value of the support foot, robot can produce the movement of the CoM in Z axis, which the classical model of the LIPM can generate this type of the movements. This type of the movement can produce a little jumping which diminishes foot collisions with the ground and results more stable turn behavior. The Fourier Series equations that leg extension trajectory is formulated below “(4)”.

$$\gamma = A_{ex} \,.\, sin(w_{ex}\, t) + C_{ex} \quad W_{ex} = W_{hx} \qquad (4)$$

The ex index stands for extension, A_{ex} is constant coefficient for generating signal. Also C_{er} is signal offset. Like the previous equations , the movement frequency of FS is equal to other behaviors, so the $W_{ex=}\ W_{hx}$.

A_{ex} and C_{ex} are the two parameters of the model of the Leg extension generator which the value of them must be found.

A. *Posture Control feedback*

In this study a simple posture control feedback is also added to make the behavior more robust against external disturbances, such as uneven ground and collisions with obstacles. The feedback is calculated using a filtered value of the accelerometer in the x direction (front); it is based on the rUNSWift Team Report 2010[12]. Equation (5) shows how to calculate the feedback values.

$$filAccelX = A * filAccelX + (A - 1) * accelX * B$$

A and B are parameters of the filtering. $filAccelX$ is summed to two hip pitch joints, to balance the torso. To do so, when the robot is falling to the front, the accelerometer will have a positive value that is added to the hip pitch joints, making the legs to move forward, to compensate. The inverse is also true, when the robot is falling backwards.

B. *Hill Climbing For Optimizing parameters 0n the real robot*

The model for changing learned trajectories has 5 parameters. The proper value of these 5 parameters is found by using hill climbing optimization. As an instance, turn in place on the real NAO was achieved with K value of 0.3. NAO robot could turn in place 360 degree in 8s stably and average body speed was around 45 degree/s. “Fig. 5” shows clock-turning obtained from GA search in simulation and after adaptation on the NAO Robot while performing clock-turning behavior.

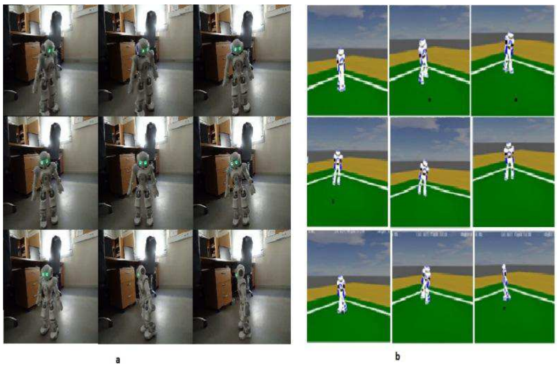

Fig.5. A) NAO Robot was adapted to do clock-turning by using simulation results in lower amplitude: B) Simulated NAO robot follows the learned nominal trajectory to do clock-turning

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